

LETTER TO THE EDITOR

Exoplanets transmission spectroscopy: accounting for eccentricity and longitude of periastron

Superwinds in the upper atmosphere of HD209458b?

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ABSTRACT

Context. A planet transiting in front of the disk of its parent star offers the opportunity to study the compositional properties of its atmosphere by means of the analysis of the stellar light filtered by the planetary atmospheric layers. Several studies have so far placed useful constraints on planetary atmospheric properties using this technique, and in the case of HD209458b even the radial velocity of the planet during the transit event has been reconstructed opening a new range of possibilities.

Aims. In this contribution we highlight the importance to account for the orbital eccentricity and longitude of periastron of the planetary orbit to accurately interpret the measured planetary radial velocity during the transit.

Methods. We calculate the radial velocity of a transiting planet in an eccentric orbit.

Results. Given the larger orbital speed of planets with respect to their stellar companions even small eccentricities can result in detectable blue or redshift radial velocity offsets during the transit with respect to the systemic velocity, the exact value depending also on the longitude of the periastron of the planetary orbit. For an hot-jupiter planet, an eccentricity of only $e=0.01$ can produce a radial velocity offset of the order of the km/s.

Conclusions. We propose an alternative interpretation of the recently claimed radial velocity blueshift (~ 2 km/s) of the planetary spectral lines of HD209458b which implies that the orbit of this system is not exactly circular. In this case, the longitude of the periastron of the stellar orbit is most likely confined in the first quadrant (and that one of the planet in the third quadrant). We highlight that transmission spectroscopy allows not only to study the compositional properties of planetary atmospheres, but also to refine their orbital parameters and that any conclusion regarding the presence of windflows on planetary surfaces coming from transmission spectroscopy measurements requires precise known orbital parameters from RV.

Key words. Techniques: spectroscopic; Planets: atmospheres; Planets: individual: HD209458b

1. Introduction

The first proof of the existence of an exoplanetary atmosphere was given by Charbonneau et al. (2002), once they succeeded in the detection of sodium absorption in the transmission spectrum of the exoplanet HD209458b. This result was obtained using the *Space Telescope Imaging Spectrograph* (STIS) on board of the *Hubble Space Telescope* (HST). In the following years several other attempts were made to detect absorption features from exoplanets atmospheres using also ground-based observatories but, until recently, they were able to place only upper limits (Moutou et al. 2001; Snellen 2004; Narita et al. 2005). Sodium detection from the ground was first achieved for HD189733b by Redfield et al. (2008) and later confirmed in HD209458b by Snellen et al. (2008) who found Na levels which matched HST values found by Sing et al. (2008). Additionally Sing et al. (2010) using ground-based narrowband spectrophotometric measurements at the GTC, detected potassium absorption in XO-2b, while Wood et al. (2010) detected sodium absorption in WASP-17b by means of transmission spectroscopy at the VLT. Recently Snellen et al. (2010) presented further ground-based detection of CO absorption lines in the atmosphere of HD209458b. Their refined analysis allowed to isolate for the

first time the doppler shift of the planetary spectral lines during the transit, allowing a direct determination of the masses both of the star and the planet, in the same manner as done for double lined eclipsing binaries. In the course of their analysis, Snellen et al. (2010) also noticed that the CO planetary absorption lines appeared blueshifted with respect to the systemic velocity of the host star, a fact that was attributed to the presence of superwinds on the planetary surface, flowing from the day to the dark side of the planet and crossing both its equatorial and polar regions. However, the planetary orbit of HD209458b was assumed to be perfectly circular. The aim of this contribution is to analyze which consequences has the presence of a non-null planetary orbital eccentricity on transmission spectroscopy measurements. Even if a residual small orbital eccentricity is present the velocity of the planet during the transit can be expected to be offset with respect to the systemic velocity, and by a significant amount given the large orbital speed of the planet, as demonstrated in Sect. 2. In Sect. 3, we discuss the particular case of HD209458b. Finally in Sect. 4, we summarize our results and conclude.

2. Transmission spectroscopy of an eccentric transiting planet

We assume a two body system composed of a planet and its host star. The radial velocity RV of the planet with respect to the barycenter of the system is given by (e.g. Hilditch 2001):

$$RV = \frac{(2\pi)^{1/3}}{P^{1/3}} \frac{(G)^{1/3} m_s \sin(i)}{\sqrt{1-e^2} (m_s + m_p)^{2/3}} \left(\cos(\omega + f) + e \cos \omega \right), \quad (1)$$

where f is the true anomaly, e is the eccentricity of the orbit, and i is the inclination with respect to the plane of the sky, m_s and m_p are the masses of the star and of the planet, ω is the longitude of the periastron of the planetary orbit, P is the orbital period, and G the gravitational constant. Isolating the terms dependent on the eccentricity and the longitude of the periastron and grouping all the others in the constant \tilde{K} we obtain:

$$RV = \tilde{K} \frac{\cos(\omega + f) + e \cos \omega}{\sqrt{1-e^2}}. \quad (2)$$

Once the planet crosses the line of sight of the observer the term dependent on the true anomaly is exactly null, then the radial velocity of the planet in that moment (RV_0), with respect to the barycentric radial velocity, is given by:

$$RV_0 = \tilde{K} \frac{e \cos \omega}{\sqrt{1-e^2}}. \quad (3)$$

This velocity is null only if the eccentricity is null or if the longitude of the periastron equals 90° (or 270°). Assuming $m_s = 1 M_\odot$, $m_p = 1 M_{jup}$, $i = 90^\circ$, $P = 3$ days and $e = 0.01$ we can derive the following upper limit for RV_0 given that $|\cos \omega| \leq 1$:

$$|RV_0| \leq 1.48 \text{ km/s}. \quad (4)$$

This result is totally due to the fact that the orbital speed of the planet is much larger than that one of its stellar companion, given its much smaller mass. Since transmission spectroscopy allows to sample only a small portion of the planetary orbit close to the mid-transit point, all the measurements acquired during the transit would appear to be offset with respect to the systemic velocity as represented in Fig. 1. Then, considering the case of an hot-jupiter, even a small eccentricity can produce a radial velocity offset of the order of the km/s (depending also on the value of the longitude of the periastron). This offset can be either blueshifted or redshifted. If the eccentricity of the system is completely neglected, assuming that the orbit is exactly circular, this radial velocity offset may be interpreted as having a different physical origin.

3. The case of HD209458b

As reported in the introduction, transmission spectroscopy was applied to the case of HD209458b by several authors in the past placing useful constraints on the abundances of different elements in its atmosphere. Recently Snellen et al. (2010), presented a refined procedure by means of which the orbital motion of the planet during the transit was unveiled for the first time through the analysis of the doppler effect of CO absorption lines. The signal they detected appeared blueshifted with respect to the systemic velocity of the host star by around 2 km/s and the uncertainty estimated by the authors was 1 km/s. The authors then interpreted this blueshifted signal as the evidence that superwinds are flowing on the surface of the planet, from

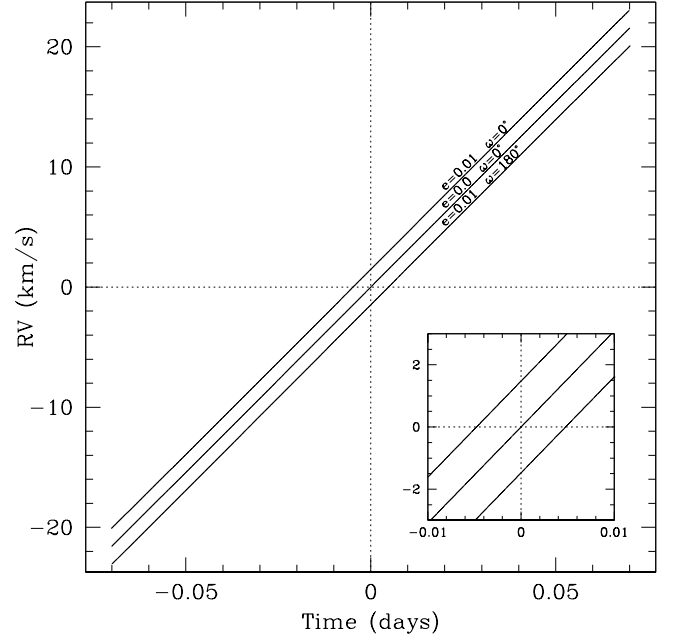


Fig. 1. The continuous lines represent the planetary radial velocity during the transit for different values of the eccentricity (e) and the longitude of periastron (ω). In this figure we assumed $m_s = 1 M_\odot$, $m_p = 1 M_{jup}$, $i = 90^\circ$, $P = 3$ days. The dotted lines indicate the mid-transit point and the systemic velocity. The box in the lower right corner is a magnified view close to the mid-transit point.

the dayside to the darkside and crossing both the equator and the poles.

This conclusion was drawn on the basis of the assumption that the orbit of HD209458b is perfectly circular. High precision radial velocities allow to conclude that the eccentricity of this system is consistent with zero within the uncertainties (Laughlin et al. 2005). In particular, Laughlin et al. (2005) pointed out that: “even when the orbit underpinning a data set is circular, e computed from an ensemble of bootstrap trials will have a characteristic nonzero value”. Nevertheless considering the uncertainties a residual small eccentricity cannot be ruled out a priori (Kipping 2008) and in the last years this was in fact a matter of large debate. Winn et al. (2005), analyzing high-precision radial velocities of the host-star, photometry and timing of the secondary eclipse, obtained for the eccentricity and longitude of periastron of the star (ω_s) the values $e = 0.0147 \pm 0.0053$ and $\omega_s = 84^\circ \pm 11^\circ$. If these mean values are used in Eq. 3, we obtain an expected blueshifted signal equal to $RV_0 = 0.21$ km/s. However, considering the 90% upper confidence limits ($e \cos \omega = 0.0049$) reported by Winn et al. (2005) we derive that RV_0 could be as high as $RV_0 = 0.68 / \sqrt{1-e^2}$ km/s. Similarly, Deming et al. (2005) derived that the secondary eclipse occurs at the midpoint between transits within 21 min ($3-\sigma$). This translates into an upper limit for the expected radial velocity offset equal to $RV_0 = 0.91 / \sqrt{1-e^2}$ km/s. These estimates appear still consistent with the observed blueshifted signal considering the uncertainties of the observations.

Then at present, given the large sensitivity of the mechanism here presented on the orbital eccentricity, and given the uncertainty of the measurements, it is questionable if other mechanisms like superwinds should be invoked to account for the ob-

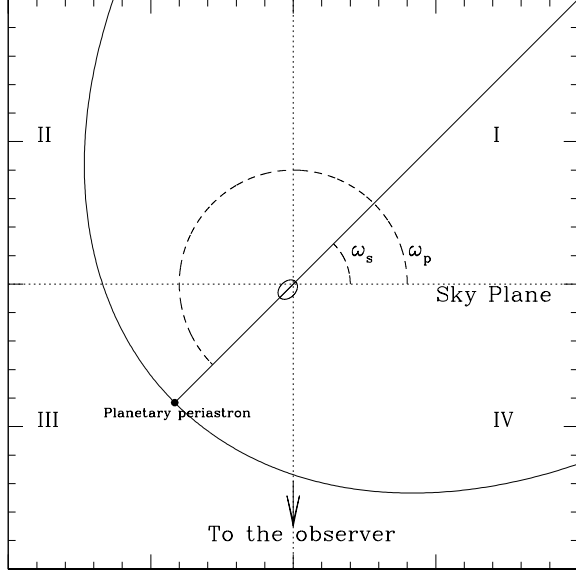


Fig. 2. Schematic representation of the orbit of the planet (large ellipse) and the orbit of the star (small ellipse), with the definition of the quadrants and of the longitude of periastron of the star (ω_s) and of the planet (ω_p). The dotted horizontal line indicates the plane of the sky, whereas the dotted vertical line the direction to the observer (arrow).

servations. As explained by Deming et al. (2005), even a dynamically significant eccentricity ($e \sim 0.03$) could be still in agreement with their $3\text{-}\sigma$ limit, despite requiring a rather good alignment of the apsidal line with the line of sight $|\omega - \pi/2| < 12^\circ$.

If totally attributed to the eccentricity, the observed blueshift would imply that the longitude of the periastron of the planet (ω_p) should lie either in the second or in the third quadrant, and consequently that one of the star ($\omega_s = \omega_p + 180^\circ$) either in the fourth or in the first quadrant respectively (see Fig. 2). Despite the large uncertainty, Winn et al. (2005) report $\omega_s = 84^\circ \pm 11^\circ$ ($1\text{-}\sigma$). Taken together, the above considerations reinforce the idea that the longitude of the periastron of the star should lie most likely in the first quadrant (and that one of the planet in the third).

4. Conclusions

Thanks to the large orbital speed of planets with respect to their stellar companions, transmission spectroscopy allows not only to constrain the properties of the atmosphere of a transiting planet, but also offers an alternative mean to refine its orbital parameters. For the eccentric planet GJ436b ($P = 2.6438986$ days, $e = 0.15$, $\omega_s = 351^\circ$) we expect a redshifted radial velocity offset equal to 11.68 km/s. For the particular case of HD209458b, nominally almost half of the blueshifted signal reported by Snellen et al. (2010) could be explained assuming that the orbital eccentricity of the system is not exactly null (just at the percent level) considering the limits imposed by transit timing of the secondary eclipse given by Deming et al. (2005). However, given the uncertainty of the measurements of Snellen et al. (2010), our estimates appear still consistent with the observations. Once attributed to the eccentricity, the blueshifted signal together with radial velocity measurements of the host star, allow to confine the longitude

of the periastron of the star in the first quadrant (and that one of the planet in the third quadrant).

Finally, it should be also noted that any conclusion regarding the presence of windflows on planetary surfaces coming from transmission spectroscopy measurements requires precise known orbital parameters from RV.

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